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LIFE CYCLE SUSTAINABILITY ASSESSMENT

Life cycle assessment as a decision support tool for bridge procurement: environmental impact comparison among five bridge designs

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Abstract
Purpose The conventional decision-making for bridges is mostly focusing on technical, economical, and safety perspectives. Nowadays, the society devotes an ever-increased effort to the construction sector regarding their environmental performance. However, considering the complexity of the environmental problems and the diverse character of bridges, the related research for bridge as a whole system is very rare. Most existing studies were only conducted for a single indicator, part of the structure components, or a specific life stage.
Methods Life Cycle Assessment (LCA) is an internationally standardized method for quantifying the environmental impact of a product, asset, or service throughout its whole life cycle. However, in the construction sector, LCA is usually applied in the procurement of buildings, but not bridges as yet. This paper presents a comprehensive LCA framework for road bridges, complied with LCA ReCiPe (H) methodology. The framework enables identification of the key structural components and life cycle stages of bridges, followed by aggregation of the environmental impacts into monetary values. The utility of the framework is illustrated by a practical case study comparing five designs for the Karlsnäs Bridge in Sweden, which is currently under construction.
Results and discussion This paper comprehensively analyzed 20 types of environmental indicators among five proposed bridge designs, which remedies the absence of full spectrum of environmental indicators in the current state of the art. The results show that the monetary weighting system and uncertainties in key variables such as the steel recycling rate and cement content may highly affect the LCA outcome. The materials, structural elements, and overall designs also have varying influences in different impact categories. The result can be largely affected by the system boundaries, surrounding environment, input uncertainties, considered impact indicators, and the weighting systems applied; thus, no general conclusions can be drawn without specifying such issues.
Conclusions Robustly evaluating and ranking the environmental impact of various bridge designs is far from straightforward. This paper is an important attempt to evaluate various designs from full dimensions. The results show that the indicators and weighting systems must be clearly specified to be applicable in a transparent procurement. This paper provides vital knowledge guiding the decision maker to select the most LCA-feasible proposal and mitigate the environmental burden in the early stage.

Keywords Bridge LCA · Carbon footprint · CO_2 equivalent emission · Environment · Global warming potential · LCA for construction · Sustainable construction · Life cycle assessment

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1 Introduction

In the construction sector, design for better environmental performance has attracted an ever-increased concern from the public and stakeholders. The construction industry as the largest industrial sector consumes 25–40 % of energy consumption and up to 50 % of waste generation in Organization for Economic Co-operation (OECD) countries (UNEP 2003; Du 2012). The decisions made in early design stages

regarding material choices and design types affect the environmental performance of all structures in a life cycle perspective, especially for those with long life spans, diverse compositions, and diverse life cycle measures, such as bridges. However, in contrast to the building sector, only technical and economic aspects are considered in current bridge procurement processes, while the environmental performance of competing designs is neglected since the assessment methodology is too vague and imprecise (Du and Karoumi 2013).

Life Cycle Assessment (LCA) is a comprehensive, standardized, and internationally recognized approach for quantifying all emissions, resource consumption, and related environmental and health impacts linked to a service, asset, or product (Treloar et al. 2000; Baumann and Tillman 2004; ISO 2006; ILCD Handbook 2010). An explicit state-of-the-art survey (Du and Karoumi 2014) showed that LCA is rarely applied holistically in bridge procurement, despite various attempts to implement it since pioneering studies by Horvath and Hendrickson (1998) and Widman (1998). Although several recent research studies attempted to perform the holistic life cycle approach on bridges (European SBRI project 2013; Safi et al. 2014b); due to the complexity of the environmental problems and the diversity of bridge structures, most previous studies either only considered a single indicator, one or a few structural components, or a specific life stage. For example, Widman (1998) confined the study scope on three selected air emissions of CO_2, CO, and NO_x; Itoh and Kitagawa (2003), Martin (2004), Collings (2006), and Bouhaya et al. (2009) limited the study on the energy consumption and CO_2 emissions; Itoh and Kitagawa (2003) excluded the end of life stage (EOL); and Gervásio and Simões da Silva (2008) limited the study scope within the material acquisition to the gate of the factory due to lack of data. However, environmental sustainability concerns not only global warming but also other environmental impacts that are relevant to chemical pollution and depletion of natural resources, which do not co-vary with the climate change impact; thus, the environmental impact analyses focusing exclusively on the global warming potential will not provide a full profile of its potential environmental impact (Laurent et al. 2012). Therefore, among various existing LCA methodologies for interpreting the environmental mechanisms (Thiebault et al. 2013; Du and Karoumi 2014), this paper conducts the study based on the most comprehensive LCA methodology of ReCiPe (H) (Goedkoop et al. 2009), which is a combined method from Eco-indicator 99' and CML 2002 with up-to-date impact categories (ILCD Handbook 2010). The analysis covers more than 1000 substances, within which 7 types of air emissions are selected to be further present in the results. Besides, the Cumulative Energy Demand (CED) and 12 mid-point impact categories are particularly investigated, which remedies the absence of full spectrum of environmental indicators in the current state-of-the-art. Furthermore, two monetary weighting systems are applied to the characterized mid-point environmental impacts to convert them to appropriate monetary values, particularly for the Swedish conditions. The results with these two monetary weighting systems will be compared.

The paper introduces a generalized, comprehensive LCA framework for road bridges, by identifying the key life cycle stages and structural components related to their environmental impact. Several issues are outlined, including the determination of critical structural components, aggregation of the environmental impacts into monetary values, and effects of variations in steel recycling rates. The utility of this bridge LCA framework is illustrated by comparing five technically feasible designs for the Karlsnäs Bridge in Sweden, each with 320-m length and 19-m width. This case study implements the knowledge of LCA into practice, with seeking the issues of how to determine the suitable bridge design solutions regarding the environmental performance. The study can provide vital reference knowledge to guide the decision-making for selecting the most LCA-feasible bridge proposal, thus enable the authority to mitigate the environmental burden of various structural components in the early planning stage, from the full life cycle perspective.

2 The bridge LCA methodology and framework

Du and Karoumi (2014) presented a systematic LCA framework for modeling the whole life cycle for railway bridges, which enables to quantify the cumulative energy consumption and potential impact related to human health, natural environment, and resources. Considering the structural relevance between a road bridge and a railway bridge, this framework is presented in this paper for road bridges, with adjustment of considered structural components and maintenance schedules, which is further illustrated in this section and Table 1. The framework enables identification of the main structural components and life cycle stages that affect environmental performance, by covering each of their elements of both the superstructure and substructure, see the scope set in Fig. 1. The associated environmental releases of the construction material are modeled by the life cycle inventory (LCI) data, which exhaustively comprises the necessity upstream processing background. The aggregated LCI data which represents the detailed manufacture processing and distribution information are further assigned into the bridge based on the defined functional unit, which is eventually imported as the input into the analysis. To facilitate the analysis, the life cycle framework of a road bridge can be separated into four stages: material manufacture stage, construction stage, use and maintenance stage, and end of life, as illustrated below.

2.1 Material manufacture phase

This phase encompasses all the upstream processes of each material used to construct the bridge, from the extraction of

Table 1 Major life cycle measures applied to beam bridges in Sweden

Action description	Action time		Reference target quantity		
	Interval	Fixed years	%	From	Unit
Superficial inspection	1		100	Total bridge area	m^2
General inspection	3		100	Total bridge area	m^2
Major inspection	6		100	Total bridge area	m^2
Cleaning salt and gravel from the bridge	1		100	Total bridge area	m^2
Cleaning and rodding of the drainage system	1		100	Drainage system points	set
Cleaning vegetation and other impurities from the bridge	1		10	Total bridge area	m^2
Bridge seats and bearings repair	20		100	Bearings number	set
Bearings replacement		60	100	Bearings number	set
Slopes and cones dressing	20		50	Slopes and cones area	m^2
Improving paintwork of the steel superstructure		25	20	Painted area	m^2
Repainting the steel superstructure		50	100	Painted area	m^2
Improving paintwork of the steel superstructure		75	30	Painted area	m^2
Bridge deck repair	35		20	Superstructure area	m^2
Edge beam concrete repair		20	30	Edge beam length	m
Edge beam concrete repair		40	40	Edge beam length	m
Edge beam replacement		60	100	Edge beam length	m
Edge beam impregnation	20		100	Edge beam length	m
Waterproofing supplementation	10		10	Paved area	m^2
Waterproofing replacement	35		35	Paved area	m^2
Wearing course adjustment	10		20	Paved area	m^2
Wearing course replacement	35		100	Paved area	m^2
Railings repainting	20		100	Parapets' length	m
Railings replacement	60		100	Parapets' length	m
Expansion joint refreshments	15		100	Expansion joint length	m
Expansion joint replacements		50	100	Expansion joint length	m
Drainage system outlet replacements	10		100	Drainage system points	set
Drainage system refreshments	10		100	Drainage system points	set
Demolition and landscaping		100	100	Total bridge area	m^2

raw materials from ground until products are ready for use at the factory gate (Du and Karoumi 2014). To model the impact of this phase, a life cycle inventory database with unit environmental profiles for each relevant material is applied, which provides data on associated releases of thousands of substances that are then aggregated into mid-point impact categories, as illustrated in Fig. 1. This initial phase is found to be responsible for the largest environmental burden throughout the whole life cycle of a bridge.

2.2 Construction phase

The environmental impacts associated with this phase are the energy consumption and emissions associated with use of the construction machinery, such as the earthwork excavators, scaffoldings, compactors, dumpers, and cranes. The transportation of materials and water consumption at the construction site are not included due to uncertainties. The most challenging issues in this phase are the lack of sufficient on-site information, notably the scarcity of historical data on energy consumption by the construction machines, and the difficulties particularly in early design stages in predicting the construction methods that will be applied and the activities involved. Thus, in this paper, the fuel consumption for the primary material transportation is modeled by truck and ship lorry from the potential supplier to the site. The energy consumption is assumed to be equivalent to approximately 0.1 L diesel per m^3 mass of material moved (in accordance with Hammervold et al. 2011).

2.3 Maintenance and use phase

This phase takes account of various future scenarios, which is the longest stage for bridges during the expected design life. In particular, the well-planned maintenance scenarios can efficiently prolong the service life, thus improve the

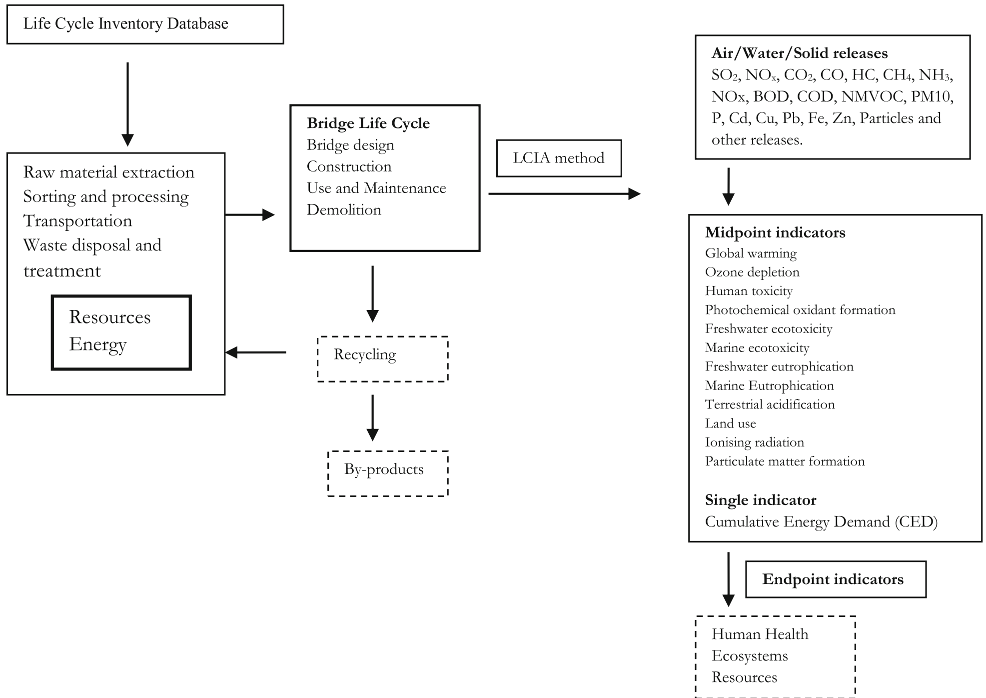


Fig. 1 Scope and flow chart of the bridge life cycle study

environmental performances in whole life perspective. Based on the historical statistics and personal communication with the experts in this field, a list of general scheduled repair activities for various structural components is recommended in Table 1 (Safi et al. 2013). Regardless of the bridge type, several maintenance activities are commonly performed, including cleaning the bridge deck, bearing replacement, repainting steel section, railing, and edge beam replacement. However, Du and Karoumi (2013) addressed that the realistic maintenance schedule and repair intervals are influenced by the budget plan, periodic inspection, and material deterioration conditions.

2.4 End of life phase

The EOL phase intends to model the future waste treatment scenarios based on today's technology, which inevitably involves high uncertainties due to the possible technology improvement after 100 years' service life. The environmental impacts in this phase include the energy consumed during several activities, including demolition of the structure, the sorting, transportation, and final treatment of the generated wastes, which may be reused, recycled, incinerated, or placed in landfills. Recycling in this stage is likely to be environmentally beneficial by reducing consumption of original materials and associated emissions. The steel used is fully recyclable. However, estimating proportions that are recycled during the EOL stage in practice or tracing the consequent life extensions is far from straightforward. In a contribution from the *stålets kretslopp* (steel life cycle) research program focusing on ways to increase steel recycling, Ekerot (2003) estimated that 60 to 65 % of the steel produced globally is made from virgin iron ore and the other 35 to 40 % from scrap. The simple "cutoff" method (Ekvall and Tillman 1997; Nicholson et al. 2009), which recommends that each product should only be assigned the environmental impacts directly caused by that product, is applied for allocation issues, to avoid including impacts not directly related to the products concerned. Based on this consideration, here, the energy and raw material savings from the steel recycling are counted in the initial material manufacture phase through the aggregated LCI data by EcoInvent v2.2, which represents the average manufacture situation in Europe by a mixture of 63 % primary and 37 % secondary steel from the electric furnace. The waste concrete is assumed to be crushed for further use as aggregate in road construction. Crushing waste concrete to produce a ton of aggregate consumes 16.99 MJ diesel and 21.19 MJ electricity under the Swedish condition (Stripple 2001).

3 Monetary evaluation of environmental impacts

LCA modeling can result into a wide range of impacts associated with human health, ecosystem quality, and resources, which are not straightforward for stakeholder and decision makers to illustrate and assess at the governing level. In order to comprehensively aggregate the impacts for an intuitive comparable set, weighting is adopted to convert the impacts into monetary values with common unit. However, weighting of environmental

impacts is being debated in LCA. As the ISO14040 standards (2006) and ILCD Handbook (2010) pointed, value-based weighting is not permitted for comparative analyses that support decisions in open tendering processes. Nevertheless, Ahlroth et al. (2011) and Ahlroth and Finnveden (2011) addressed that weighting is still widely used to meet practitioners and decision makers need, as illustrated in several research studies recently, e.g., Mahgoub et al. (2010), Contreras et al. (2009), Kiwjaroun et al. (2009), Liu et al. (2010), Tsoutsos et al. (2010), and Zackrisson (2005); it is recommended to use several weighting sets and compare the outcomes to reduce risks of overlooking important factors. More specifically, Ahlroth et al. (2011) comprehensively discussed the feasibility of evaluating the economic value of environmental impacts in the whole life perspectives. They showed that one way to include external environmental costs in life cycle costing (LCC) is to use monetary-weighted results obtained from environmental system analysis (such as LCA); several examples of such applications are available in the literature (Carlsson Reich 2005; Nakamura and Kondo 2006; Kicherer et al. 2007; Lim et al. 2008; Hunkeler et al. 2008). In this study, two monetary weighting systems, Ecovalue08 with updated Ecovalue12 weightings (Ahlroth and Finnveden 2011; Ahlroth et al. 2011; Finnveden et al. 2013) and Ecotax02 (Finnveden et al. 2006), are adopted and compared. The Ecovalue monetary weighting set has been developed for evaluating mid-point environmental impacts based on willingness-to-pay, with particular focus on Swedish conditions, while the Ecotax set is based on environmental taxes and fees levied by a focal society. Table 2 presents these two weighting sets, it should be noted that some impact categories cannot be weighted, due to the limitations of the available weighting factors.

4 Case study: comparison of five proposed designs for the Karlsnäs Bridge

4.1 Background

In 2013, the Swedish Road Administration (Trafikverket) announced plans to build a new road bridge, Karlsnäs Bridge, in Västra Götaland, Sweden, as part of a new road corridor anticipated to carry an average daily traffic volume of approximately 10,000 vehicles. The bridge is 320 m long and 22.5 m wide, carrying two traffic lanes in each direction. Trafikverket decided to procure this bridge through a design-build (D-B) tendering process (Safi et al. 2014a). For the purpose of this paper, five design proposals were developed, as illustrated in Table 3: (1) a steel box girder composite bridge, (2) a steel I-girder composite bridge, (3) and (4) post-tensioned concrete box girder bridges, and (5) a balanced cantilever concrete box girder bridge.

The design selection in such processes may be affected by several factors in early planning stages, including LCC, the available construction methods, ease of maintenance, geotechnical conditions, and strength of concrete (Habert et al. 2012). Comparing to the concrete bridges, steel-concrete composite bridges are lighter, easier to be erected, as well as consume less formworks. Furthermore, when the concrete girder in the span center is replaced by steel box girders, the self-weight is reduced and the span length can be extended (Nakamura et al. 2002).

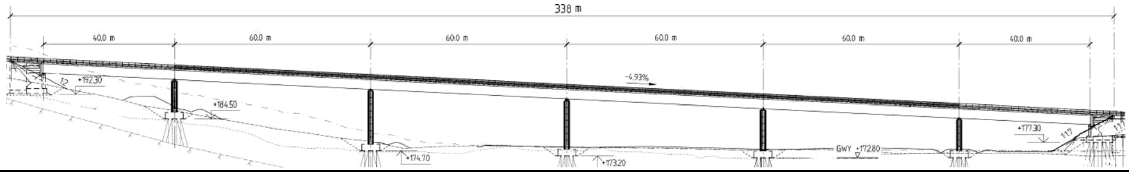
This paper is sought to seek how the type of bridge design affects the environmental performance. The LCA analysis covers the whole bridge from the superstructure of slab, beam, and structural steel section to the substructure of columns, abutments, and the foundation. The whole bridge of the same span length and width is chosen as the functional unit under the identical design criterion of 100-year life span.

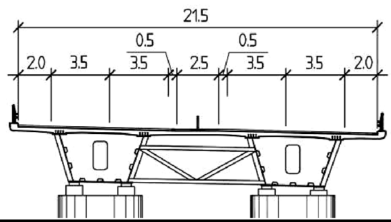
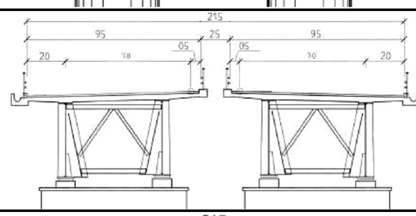
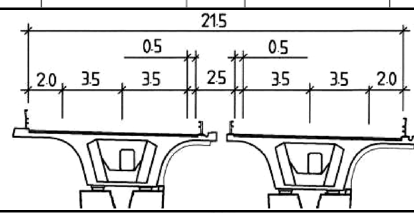
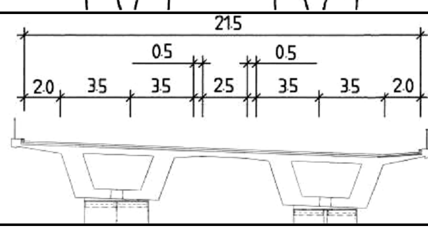
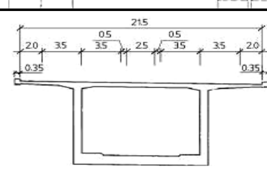
Table 2 Characterized environmental impact categories and monetary weighting factors (Ahlroth and Finnveden 2011; Ahlroth et al. 2011; Finnveden et al. 2006; Finnveden et al. 2013)

Environmental impact category	Acronym	Unit	Ecovalue (SEK)	Ecotax02 (SEK)
Global warming	GWP	kg CO_2eq	2.85	0.63
Ozone depletion	ODP	kg CFC-11 eq	–	1200
Human toxicity	HTP	kg 1,4-DB eq	2.81	1.5
Photochemical oxidant formation	POFP	kg NMVOC	16	156
Particulate matter formation	PMFP	kg PM10 eq	273	–
Ionizing radiation	IRP	kg U235 eq	–	–
Terrestrial acidification	TAP	kg SO_2eq	30	15
Freshwater eutrophication	FEP	kg P eq	670	–
Marine eutrophication	MEP	kg N eq	90	12
Terrestrial ecotoxicity	TETP	kg 1,4-DB eq	–	176
Freshwater ecotoxicity	PETP	kg 1,4-DB eq	–	92
Marine ecotoxicity	METP	kg 1,4-DB eq	12	0.3

The P in each acronym refers to potential

Table 3 Illustrations and specifications of the five proposed designs



Proposal No.	Description	Cross-Section Details	Remarks
1	**Composite bridge** One bridge, two steel boxes		6 Spans: 4×60m + 2×40m Construction method: Launching Superstructure depth: 3 m
2	**Composite bridge** Two bridges, Two steel I-girders per bridge		6 Spans: 4×60m + 2×40m Construction method: Launching Superstructure depth: 3 m
3	**Concrete box girder bridge** Two bridges, one pre-stressed concrete box per bridge		6 Spans: 4×60m + 2×40m Construction method: Fixed scaffolding Superstructure depth: 3 m
4	**Concrete box girder bridge** One bridge, two pre-stressed concrete boxes.		6 Spans: 4×60m + 2×40m Construction method: Fixed scaffolding Superstructure depth: 3 m
5	**Concrete box girder bridge** One bridge, one concrete box girder		4 Spans: 2×115m + 2×45m Construction method: Balanced cantilevering Superstructure depth: 7.4 m to 3 m

4.2 Construction methods

The decisions on the initial design of the bridge can substantially affect the selection of material and construction methods, thus influence the environmental performance over its long life cycle span. Here, three construction methods for five proposals are detailed below.

4.2.1 Launching method

The most common method to build a steel composite bridge is to first launch the steel girders and then cast the bridge deck on site (Höglund 1992). Here, both of the steel girders in proposal 1 and proposal 2 will be erected by launching, which allows the structure to be preassembled outside the site, then slide steadily on Teflon bearings toward its final location.

4.2.2 Scaffolding/formwork method

For the complex prestressed concrete bridges as proposals 3 and 4, the fixed scaffolding and formwork method is commonly applied, see Fig. 2. In Sweden, such concrete bridges are mostly cast in situ under the assist of formwork, which are often made by wood and steel with sufficient strength to

Fig. 2 Formwork and scaffoldings for Karlsnäs Bridge under construction (photographed by Patrik van Meer)

temporarily withstand the wet concrete until shaping into the desired outline. The scaffolding is assembled by horizontal and vertical steel tubes, which serves as a temporary platform to support the equipment, workers, and materials. Due to the additional working volume involved in the installation of the formwork and scaffolding system on-site, approximately 70 % more man hours will be needed in this construction method, comparing to the proposals 1 and 2.

4.2.3 Balanced cantilever erection method

Proposal 5 with large spans is commonly constructed by the balanced cantilever method in practice. By moving the formwork step by step, segments are casted in place by the form travelers, which enable to symmetrically erect the segments from both sides of the pier until reaching the mid-span. The method is beneficial to apply on the long span bridges, especially for these over the water, thus to avoid using scaffolding or building complex foundations under water.

4.3 Environmental inventory data

For a reliable analysis, the LCI data must explicitly cover all the direct and indirect processes linked to the whole bridge. In this paper, the implemented data referring to the average European conditions are collected from the public database Ecoinvent v2.2. Ten types of materials and processes are involved for modeling the bridge, within each enclose over thousand datasets of auxiliary materials and compound releases. The data represents the environmental impacts of production in average European conditions, supported by unit processing and related flows of air, water, and solid releases.

4.3.1 Concrete

Generally, approximately 100 to 300 kg of CO_2 is embodied in every cubic meter of concrete produced, depending on the concrete quality, which is relatively low compared with other building materials (Lemay 2011). The concrete, as a dominated material in all five design proposals, requires less maintenance comparing to the structural steel. The ready-mixed concrete C50/60 "exacting concrete," which has the most similar property from the one used in the reality, is applied in bridge LCA modeling. This concrete has 0.4 water/cement (w/c) ratio and 375 kg/m^3 cement content. The selection of concrete class is dependent on the required strength and w/c, which is governed by a varied mixture ratio for the desired properties among cement aggregates, ashes, admixture, and water.

4.3.2 Structural steel and reinforcement

The average CO_2 intensity for the steel industry is 1.9 t of CO_2 per ton of steel produced (Kundak et al. 2009). However, even for the same type of steel, the environmental performance is influenced in practice by the specific manufacturing technology involved and the percentage of recycled steel. In the first two proposals in this paper, the structural steel section as the main load bearing component, is modeled by "steel, low-alloyed, at plant" (Classen et al. 2009), quantified as 1,275 t in the steel box girder bridge proposal and 1,100 t in the steel I-girder composite bridge proposal. The data for the reinforcement rebar is obtained from Ecoinvent by the material of "reinforcing steel." In this study, the simple cutoff method is implemented in EOL, by following the method presented in Ekvall and Tillman (1997) and de Schrynmakers (2009). More specifically, instead of counting the environmental benefit from steel recycling at EOL stage, it is considered in the initial material manufacture phase by the mixture of 63 % primary with 37 % secondary steel from electric furnace route, which represents the average European production mixture condition.

Formwork are made from various materials, such as softwood, hardboard, plywood, and steel (Peters 1991). In this paper, formwork is used in all proposals but more than doubled amount for the concrete bridges, which directly contributes to an increased man hours approximately 70 % more than the steel composite bridges. The formwork in the analysis is

modeled by the Ecoinvent data of “Scandinavian softwood,” with an estimated thickness of 10 cm.

4.3.3 Steel railings

Steel railings are hot-dip galvanized after fabrication, with a standard system weight of 50 kg per meter, which is modeled by the Ecoinvent data of “electric, un-alloyed, and low-alloyed steel.”

4.3.4 Bearings

Bearings are essential devices for transferring loads and movements from the deck to the substructure and foundations of a bridge (Choo et al. 2013). There are various types of bridge bearings to suite for different mechanical condition and bridge spans. In this paper, the bearings are considered for the steel composite bridges, the prestressed concrete bridges, and the cantilever concrete bridge, see Table 4. Inventory data of ordinary steel is applied for this part of the analysis.

4.3.5 Paint

The paint considered here consists of an epoxy paint layer and anti-corrosion zinc coating required for the first two proposals to protect the surface area of the steel box and I-girders. For proposal 1, the boxes are made airtight and thus are only painted on the outside, while for proposal 2 the I-girders are painted on both sides, which result into a relatively large area on the cross beams that need to be painted. The estimated painted areas for the first and second proposals are approximately 6,050 and 10,800 m^2, respectively.

4.3.6 Transportation of materials

The construction and maintenance materials are assumed to be transported by trucks, following a sea crossing by freight ship if necessary. The simulated distances are those between the site and potential suppliers, as shown in Table 5. More specifically, it is assumed that all the concrete would be transported less than 100 km from the nearby city of Lidköping, the reinforcement 350 km from Stockholm, the steel 500 km by freight ferry then 100 km by truck from Latvia, the formwork 150 km for all proposals, and scaffolding 300 km for concrete bridges including a return transportation.

4.3.7 Diesel and electricity consumption

This study covers the diesel and electricity consumed in the building machines, both in the construction phase and in the EOL phase. In Sweden, bridges are normally built by concrete cast in situ other than precast segments. If the steel structures are used, as shown in proposals 1 and 2, they are commonly prefabricated in workshops in approximately 25-m long sections of box or I-beam, which are further welded together and launched at site. Due to the limited information, the specific energy consumption from the machinery is assumed to be approximately 0.1 L diesel burned in a building machine per m^3 mass moved (Hammervold et al. 2011). The crushing of concrete to obtain aggregates for road building in the EOL stage is assumed to consume 16.99 MJ diesel and 21.19 MJ electricity per ton (Stripple 2001).

4.4 Limitations

One limitation is realized as the insufficient information and the absence of “true” data. A number of assumptions have been made, and several scenarios are omitted in the analysis. For

Table 4 Structural components of the five proposed designs

	Unit	Proposal 1	Proposal 2	Proposal 3	Proposal 4	Proposal 5
Total bridge length	m	338	338	338	338	338
Superstructure length	m	322	322	322	322	322
Effective bridge width	m	19	19	19	19	19
Superstructure effective area	m^2	6118	6118	6118	6118	6118
Painted area	m^2	6050	10800	0	0	0
No. of spans	–	6	6	6	6	4
Total no. of supports	–	7	7	7	7	5
No. of bearings	–	28	28	28	28	10
Edge beam length	m	676	1352	1352	676	676
Parapets' length	m	676	1352	1352	676	676

Table 5 Life cycle inventories of the five design proposals

	Quantities and scenarios					
	Unit	Proposal 1	Proposal 2	Proposal 3	Proposal 4	Proposal 5
Material manufacture phase						
Concrete	m^3	6111	6111	9975	9676	10288
Reinforcement	t	834	834	1530	1484	1640
Structural steel	t	1275	1106	0	0	0
Steel parapets	t	34	68	68	34	34
Bearings	t	25	25	33	33	30
Formwork	m^2	6762	7406	15736	15736	15736
Painting	m^2	6050	10800	0	0	0
Construction phase						
Diesel consumption	L	638	636	1017	987	1050
Concrete transportation	km	100	100	100	100	100
Formwork transportation	km	150	150	150	150	150
Scaffolding transportation	km	0	0	300	300	0
Reinforcement transportation	km	350	350	350	350	350
Structural steel transportation	km	600	600	0	0	0
Parapets transportation	km	200	200	200	200	200
Maintenance phase						
Bearing replacement every 30 years	t	100	100	132	132	120
Painting improvement at 25 and 75 years	m^2	2420	4320	0	0	0
Fully repainting at 50 years	m^2	6050	10800	0	0	0
30 % edge beam repair at 20 years	m^3	51	101	101	51	51
40 % edge beam repair at 40 years	m^3	68	135	135	68	68
100 % edge beam repair at 60 years	m^3	169	338	338	169	169
Steel parapet replacement	t	34	68	68	34	34
End of life						
Diesel consumption in EOL phase	MJ	249182	249182	406740	394548	419503
Electricity consumption in EOL phase	MJ	310781	310781	507289	492082	523206

instance, during the construction phase, the diesel fuel from machinery usages and electricity consumptions on-site, are eventually replaced by the average data from literatures. The adopted LCI data in this study is retrieved from the public Ecoinvent Database, which is limited to the specific conditions. The scenario of assessing the environmental burden from on-site construction man hours, being approximately 70 % more for the concrete bridges, is excluded due to the high level of uncertainties involved. Such limitation leads to the underestimation of the impacts from construction phase. In order to improve the reliability of the analysis result, it is necessary for the authority to establish a comprehensive database archiving the on-site construction information.

4.5 The environmental impact assessment

An important choice when defining the scope of an LCA is the type of impacts to include (Finnveden and Ekvall 1998). Here, to assess the potential impacts of the five design proposals as fully as possible, considering environmental, human health, and resource dimensions, the ReCiPe (H) methodology (Goedkoop et al. 2009) is applied, which aggregates inventoried elementary flows into impact indicators. More specifically, we selected the following spectrum of indicators: 7 atmospheric emissions (CO_2, CH_4, SO_2, NH_3, NOx, NMVOC, PM_{10}), cumulative energy demand (CED), and 12 mid-point environmental impact categories. These categories are global warming (GWP), ozone depletion (ODP), human toxicity (HTP), photochemical oxidant formation (POFP), particulate matter formation (PMFP), ionizing radiation (IRP), terrestrial acidification (TAP), freshwater eutrophication (FEP), marine eutrophication (MEP), terrestrial ecotoxicity (TETP), freshwater ecotoxicity (FETP), and marine ecotoxicity (METP). NMVOC and PM_{10} refer to non-methane volatile organic compounds and particles with up to 10-μm diameters, respectively, and the “P” for all impact categories refers to potential.

4.6 Results

The full results provide data on the release of thousands of chemicals associated with the production and use of the materials. Here, we focus on presenting seven atmospheric emissions that are typically associated with the manufacture and use of construction materials (Zhang et al. 2013): CO_2 and CH_4 that strongly related to GWP; SO_2 and NO_x linked with TAP; nitrogen for FEP and MEP; NO_x and NMVOC for POFP and PM_{10} for PMFP. The results for these species, as in Fig. 3, indicate that under the 37 % steel recycling rate, each proposal can perform differently depending on the concerned emission categories but still with similar magnitude range. For emission of CH_4, SO_2, and PM_{10}, the concrete bridges would be associated with lower emission levels than the steel composite bridges by up to 30 %, but it appears the opposite for the emissions of CO_2 and NMVOC. The most contributions, by far, are dominated by the initial material manufacturing phase ranging from 72 to 94 %. Accordingly, the construction, maintenance, and EOL phases contribute relatively small percentages: up to 18, 9, and 4 %, respectively. However, during the construction phase, it indicates that the steel composite bridges are more environmentally friendly, due to their ease of erection and relatively light weights. Comparing with other proposals, the parallel double superstructure design in proposals 2 and 3 results into nearly doubling emissions in the maintenance stage, mainly resulting from the replacement of the parapets and the edge beams as illustrated in Table 5. Levels of emissions in the EOL stage appear to be negligible (ca. 1 % of the total), except for NO_x and NMVOC (ca. 4 %), primarily arising from diesel combustion, electricity consumption, and transportation.

Although the global warming potential is an important indicator, the decision maker should not omit the other impact categories for interpreting the full environmental profile (Laurent et al. 2012). This can be explained by the complexity mechanism of the environmental problems and the values of the nature from various aspects (Gustafsson 1998). Thus, to establish a full environmental profile of the concerned bridges, it is vital to cover the chemical and impact categories in the assessment as comprehensive as possible; absolute environmental impacts of each design in 12 mid-point categories and CED are presented in Table 6 and relative impacts in Fig. 4. Neither the steel composite bridges nor the reinforced concrete bridges showed absolute advantages in these frequently studied impact categories, for example, the GWP and CED. In some of the rest categories, the concrete bridge proposals appear to have lower impact than the steel composite alternatives, mainly due to the relatively high energy consumption in the initial steel manufacture. This indicates that the reduced concrete quantities and the benefits from recycling steel in the first two proposals cannot compensate for the greater energy consumption in steel manufacture. Furthermore, the benefits from selection of a concrete bridge design vary among the indicators, being up to 25 % less in HTP, 21 % less in PMFP, 32 % less in TAP, 28 % less in FEP, 26 % less in MEP, 22 % less in TETP, 13 % less in PETP, and 30 % less in METP.

In addition to the mid-point impact categories, CED is another important indicator, representing the energy consumed, directly and indirectly, during the manufacture, construction, maintenance, and dismantling of a product or service from fossil, nuclear, biomass, water, wind, and/or solar sources. Figure 5 shows the life cycle stage contribution in CED for each proposed design, which corresponds well with the previous studied indicators. Overall, the CED is found to be nearly the same among all five proposals. Besides, it has been shown that CED is largely dominated by the material manufacture phase ranging from 68 to 80 %. In the construction phase, the steel bridge proposals only represent up to 12 % while the concrete bridge proposals are up to 25 %, mainly due to the impact raised from scaffoldings and formwork usage. In the maintenance phase, the double parallel superstructure in proposals 2 and 3 contributes to nearly double CED, due to the double number of edge beams and the mean barriers are not considered in the analysis.

Figure 6 identifies the impact contributions from various bridge structural components, regarding the significance of

Fig. 3 Atmospheric emissions associated with each proposal in indicated life cycle stages

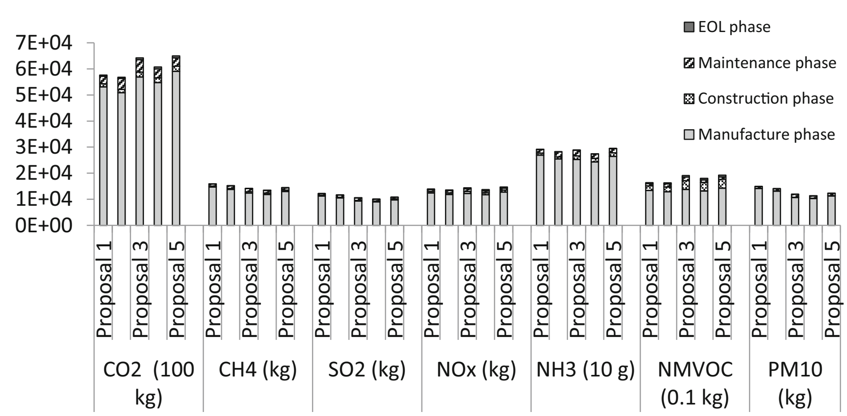


Table 6 Characterized environmental impacts of the five proposed designs with 37 % steel recycling rate

Environmental impact category	Acronym	Unit	Proposal 1	Proposal 2	Proposal 3	Proposal 4	Proposal 5
Global warming	GWP	kg CO_2eq	6.09E+06	5.99E+06	6.64E+06	6.32E+06	6.77E+06
Ozone depletion	ODP	kg CFC-11 eq	2.64E–01	2.67E−01	2.86E–01	2.72E–01	2.91E–01
Human toxicity	HTP	kg 1,4-DB eq	1.67E+06	1.70E+06	1.39E+06	1.26E+06	1.36E+06
Photochemical oxidant formation	POFP	kg NMVOC	1.93E+04	1.89E+04	2.00E+04	1.91E+04	2.05E+04
Particulate matter formation	PMFP	kg PM10 eq	1.64E+04	1.62E+04	1.35E+04	1.30E+04	1.40E+04
Ionizing radiation	IRP	kg U_{235}eq	3.18E+05	3.16E+05	3.32E+05	3.13E+05	3.36E+05
Terrestrial acidification	TAP	kg SO_2eq	2.24E+04	2.51E+04	1.77E+04	1.70E+04	1.82E+04
Freshwater eutrophication	FEP	kg P eq	3.24E+02	3.21E+02	2.42E+02	2.32E+02	2.51E+02
Marine eutrophication	MEP	kg N eq	7.64E+02	8.74E+02	6.77E+02	6.49E+02	6.92E+02
Terrestrial ecotoxicity	TETP	kg 1,4-DB 1eq	5.78E+02	5.97E+02	5.01E+02	4.63E+02	4.98E+02
Freshwater ecotoxicity	FETP	kg 1,4-DB eq	1.70E+03	1.68E+03	1.56E+03	1.47E+03	1.58E+03
Marine ecotoxicity	METP	kg 1,4-DB eq	8.90E+03	9.12E+03	6.77E+03	6.41E+03	6.93E+03

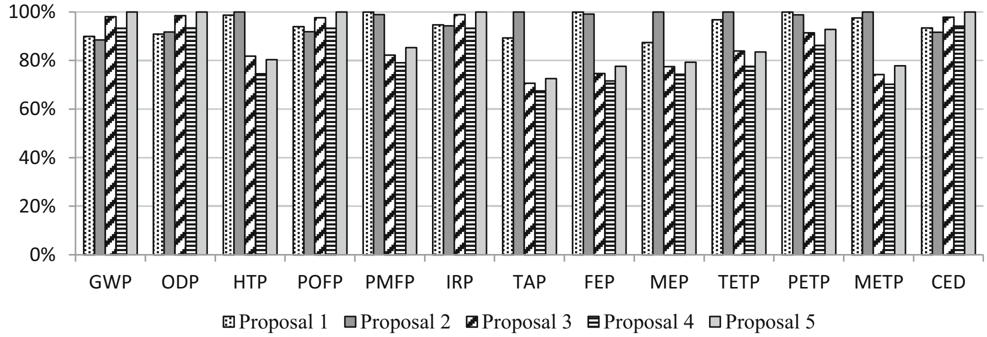
The P in each acronym refers to potential

scenarios in each life cycle stage. The results reveal that the decisive structural component and life cycle scenario is dependent on the targeted environmental impact category. Concrete manufacture is the main contributor to GWP (between 31 and 48 %), but not HTP (just 6 %). However, initial manufacture is by far the main contributor to the overall burden in every category for the concrete, reinforcement, steel, and parapet materials from 66 to 91 %, and both structural steel and reinforcement by up to 79 %. In contrast, the impact from the manufacture of bearings, painting, and use of machinery in the manufacture phase is negligible, accounting for less than 10 % of the total impact in each category. The construction stage, except taking up to 24 % in CED, also contributes to a relatively higher POCP impact, mainly due to the high level of NMVOC released by fuel combustion during the transportation of materials and operation of machinery. In the maintenance phase, only the replacement of steel bearings has a noticeable impact, accounting for up to 9 % of the burden in specific categories. In addition, the parallel double bridge superstructure of proposals 2 and 3 highly increases the impact due to the need to replace parapets. Steel manufacture is by far the main contributor to HTP with up to 83 % of the impact, due to the high associated emissions of toxic heavy metals including lead, chromium, zinc, copper, nickel, and manganese (Suh and Rousseaux 2002). In addition, transportation is a major contributor to POCP by up to 15 %, due to the high releases of volatile organic compounds and nitrogen oxides in combustion exhausts.

4.7 Sensitivity analysis

Due to the complexity of bridge structures, their long life spans, and the assumptions made, there are inevitably high levels of uncertainties in bridge LCA from various sources. Apparent differences in impacts may be misleading if the uncertainty in impacts is large enough to overwhelm any relative differences between alternatives (Baker and Lepech 2009). Therefore, the sensitivity analysis for evaluating the potential consequence of variations in key factors is important. Björklund (2002) addressed different types of sensitivity and uncertainty importance analysis. Steel and concrete as two dominant construction materials, on one hand, the concrete initially involves a lower value of embodied energy and emissions than the steel; on the other hand, the recyclable property makes the steel comparable with the concrete. Here, concrete and steel are prioritized in the sensitivity analysis to check the results reliability.

Fig. 4 The percentage comparison among the characterized impact categories, with 37 % recycling rate in structural steel and reinforcement



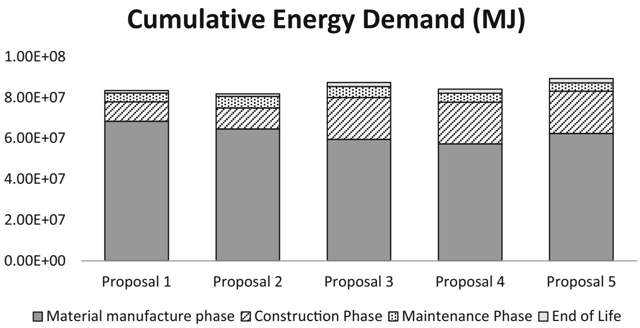


Fig. 5 The cumulative energy demand, with 37 % recycling rate in structural steel and reinforcement (unit: megajoules)

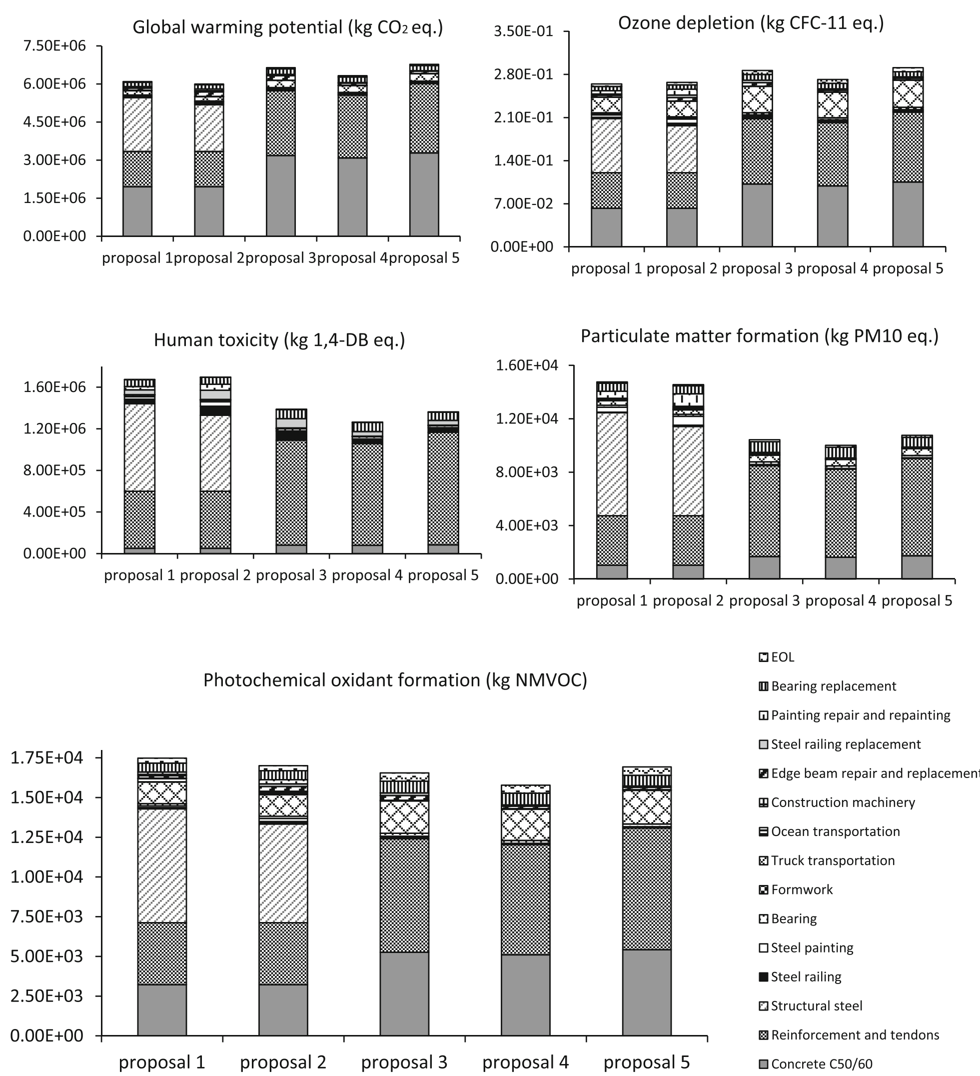
4.7.1 Steel recycling rates

The 37 % steel recycling rate as the average European condition is applied in the modeling; however, the recycling rate or technology that seems impossible today might be highly improved in the future. Hence, the effects of increasing the steel recycling rate from 37 to 100 % and reducing it to 0 % are investigated and compared, including the structural steel, the reinforcement, and tendons. The results show that the variation within this range may lead to the difference in terms of CO_2 equivalents up to 71 %, due to the changes from 2,253 to 664 kg CO_2-eq/t of the steel. Furthermore, the environmental impact of the steel composite bridges in the GWP and CED categories could be reduced by up to 45 %, see Figs. 7 and 8, which present the maximum and minimum values corresponding to 0 and 100 % recycling rate, respectively. Furthermore, when the steel recycling rate reaches to 100 %, the steel composite designs show up to 23 % advantages compare to the concrete proposal.

4.7.2 Concrete types

Concrete as one of the most utilized construction materials consists of a wide range mixture of components, which controlled by the different mixture proportions or types of their basic components, as well as the compatibility among chemical admixtures. There are various types of concrete purposed

Fig. 6 Environmental impacts of structural components and life cycle measures of the five proposed bridges (unit: kilograms)



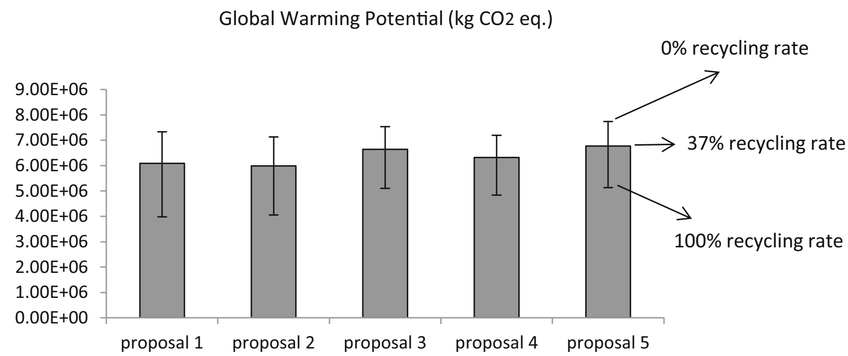


Fig. 7 GWP due to the steel recycling rate variation 0, 37, and 100 % (unit: kilograms)

for particular applications with specific strength. The data selection of concrete types requires expertise knowledge in concrete, which usually exceeds the LCA analysts' professional, hence may lead to a biased result. Here, the sensitivity analysis is performed to estimate such effects from using different concrete: concrete C25/35 and C50/60. The result in Fig. 9 shows that when using C25/30, the GWP has decreased up to approximately 22 % for the steel-concrete composite bridges and 35 % for concrete bridges, respectively. For C50/60, the steel composite bridges show advantages than the concrete bridges but it becomes opposite when using C25/30. This verifies that the possible data gap among the variety of concrete types may large enough to lead a contradictory conclusion.

4.8 Monetary valuation

The environmental costs of each design are assessed here by aggregating their characterized mid-point environmental categories using both the Ecovalue08 monetary weighting set (with updated Ecovalue12 values for global warming potential, particulate matter formation, and ecotoxicological impact indicators) and the Ecotax02 set. However, due to the limited available weighting factors, only 11 mid-point impact indicators can be aggregated, see the weighting set presented in Table 2. The results in Fig. 10 indicate that the Ecotax02 set yields lower absolute total costs for each proposal than the Ecovalue set, due to differences in the weighting principles and categories covered. However, in both cases, each proposal has a similar relative monetary value. The category of global warming is found as the most dominated impacts according to Ecovalue, while it becomes the global warming, human toxicity, and photooxidant formation from Ecotax. However, despite the differences in the two weighting sets, they provided identical rankings for the five proposals, which is consistent in a case study presented in Ahlroth and Finnveden (2011).

5 Discussion and conclusions

In the pursuit of construction sustainability, the bridge structures attract an ever-increased concern for their environmental performance, as well as their related monetary value. The previous research studies were under strong criticize that too few life cycle scenarios, insufficient structural items, or limited types of impact categories were included, which may result into a biased result. Here, a comprehensive LCA framework has been proposed, which enables to estimate the potential environmental impacts of key activities and structural components throughout the bridge whole life cycle. The paper explicitly compared five common bridge design types through the whole life cycle with the up-to-date LCA methodology ReCiPe (H). The study covered a wide range of environmental impact indicators from the substance level to the aggregated mid-point environmental impact: including 7 types of air emission substances, 12 mid-point impact categories, the

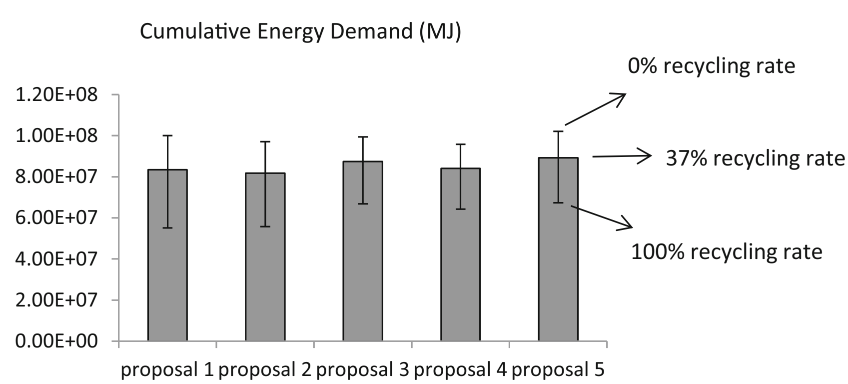


Fig. 8 CED due to the steel recycling rate variation 0, 37, and 100 % (unit: megajoules)

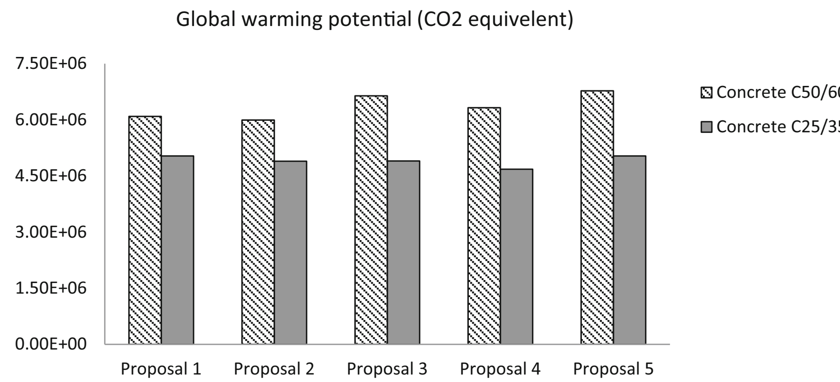


Fig. 9 GWP due to the concrete type variation (concrete C50/60, concrete C25/35)

cumulative energy demand, as well as their monetary value, which enables the analyst to obtain a full spectrum of the bridge environmental performance from various aspects. The results clearly identify the major structural and life cycle scenario contributors to the selected impact categories, and reveal the effects of varying the monetary weighting system, the steel recycling rate, and the concrete types. The issues of how the material and bridge design relating with the environmental performance were also thoroughly discussed. The analysis can provide a vital reference knowledge guiding the decision makers to select the most feasible proposal, to aid the authority mitigating the environmental burden in the early planning stage, and to recommend the environmental improvement solutions regarding the imperfect items. The main findings are concluded in the following:

First, there are inevitably inherent uncertainties from various sources. Comparing to the true data in the reality,

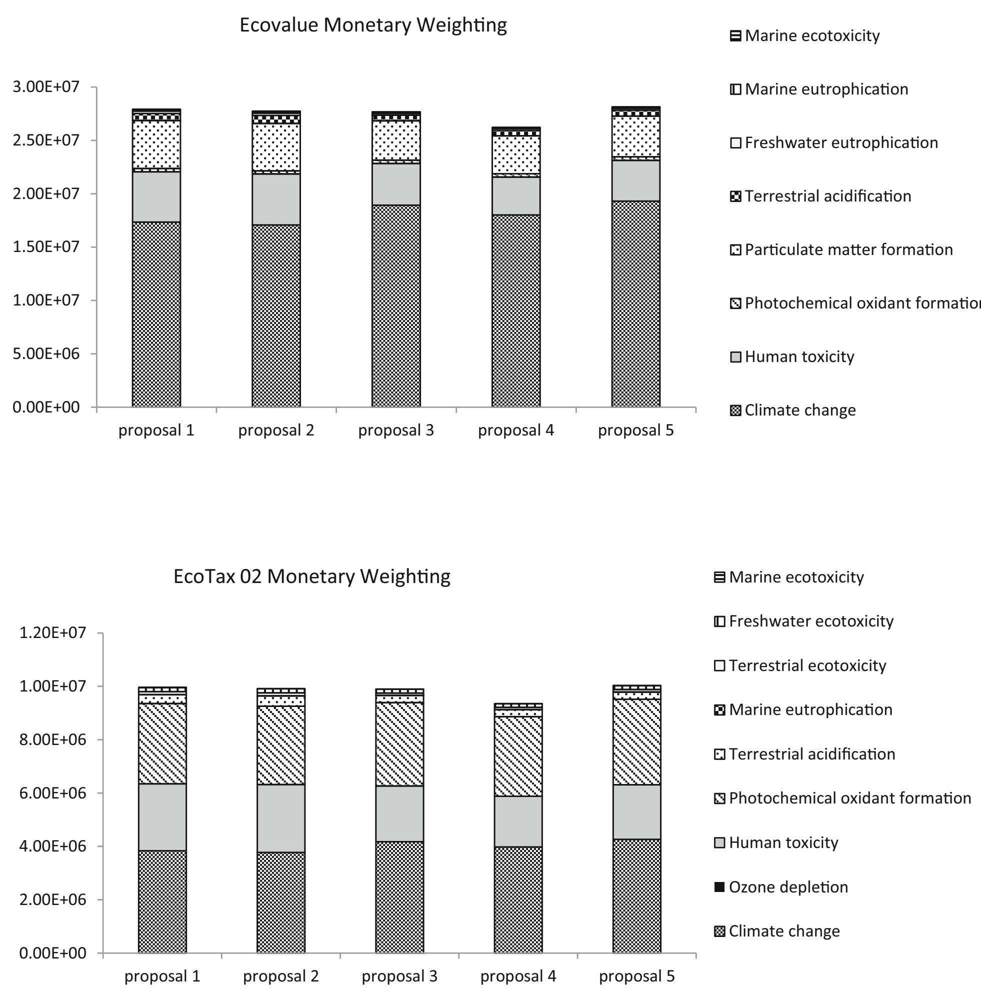


Fig. 10 Environmental costs of the five proposed bridges (SEK)

it should be noted that the data gaps in the modeling may be large enough to lead to a biased result. The conclusion may be falsified if the input data was vague, which may be due to the limitation of the data itself or the preference choices from the analysts. This paper has verified that a slight change in the input may result into a contradictory conclusion. For example, without scaffolding and formwork related scenarios in the concrete proposals, the environmental beneficial of concrete bridge design would overwhelm the steel composite ones, which is conflict to the current conclusion. Besides, this study has omitted the scenario of man hours during the construction phase, with the estimated number on-site being approximately 70 % more for the concrete bridges than for the composite bridges, which would lead to the underestimation in the results. In addition, the environmental burdens due to the traffic congestion during the maintenance activities are neglected in this specific case since they are considered to be similar for all five bridge cases. However, if taking this aspect into account in other cases, the result may change since the scenario with the shortest intervention time will be favored. Furthermore, with the average European steel recycling rate of 37 %, there is no bridge showing absolute advantages in GWP and CED, but such conclusion does not hold when increasing the recycling rate to 100 %. The sensitivity analysis pointed out that the conclusion has changed considerably when using concrete C25/30 instead of C50/60. However, the inherent uncertainties can be largely mitigated by covering sufficient amount of impact categories, structural items, and scenarios.

Second, the complex nature of environment and bridge structures have shown that without the illustration of particular prescribed conditions, it is not possible to give a definite conclusion. Mainly because of the environmental assessment can be performed at various levels of details. Even this study is carried out at the most explicit level comparing to the current state of the art, it is impossible to include all the relevant environmental indicators, scenarios, or the structural components. In this study, neither the steel composite bridges nor the reinforced concrete bridges showed absolute advantages in ordinary impact categories, such as GWP and CED. It is therefore insufficient to capture the environmental performance of individual bridge only by few selected indicators, which may result into biased conclusions. To comprehensively reflect and declare the environmental performance of the bridge, it is important to cover as many indicators as possible at the current stage. One cannot simply draw a conclusion without specifying the referred impact indicator, particular scenarios adopted or the principle through the decision-making process. The most favorable proposal in terms of one impact category is not necessarily preferable in another. Even for the same bridge, the analyzed result may vary among indicators, which heavily depend on the selected environmental criteria and the predefined study boundary. For example, proposal 4 has shown preferable performance in some specific categories; proposal 1 shows higher advantages than proposal 2 in TAP and MEP but not in other categories, while in GWP, ODP, POFP, IRP, and CED, the best proposal among design solutions is not obvious. In fact, except the observed LCA results, the decision-making in reality is largely dependent on the specific impact categories that the authority has chosen. Considering the environmental profile varies case by case, it is deemed that the relative difference among the designs is more important than the absolute values.

The environmental performance of bridges has been extensively investigated in this paper. However, not all the surveyed impacts are belonging to the same category class. In order to provide an intuitive and comprehensive result for the decision makers, this study attempted to link the economic evaluation with the environmental impacts. The monetary weighting indicates that Ecotax provides lower absolute total impacts for each proposal than the Ecovalue weightings, due to differences in the weighting principles and categories covered. Despite these differences, it has been found that two systems yielded identical rankings for the five proposals, which is in line with the conclusions from Ahlroth and Finnveden (2011). However, in both systems, no bridge design shows absolute advantages among the others. The most cost-effective bridge is not necessarily the most environmentally friendly one, due to the varied scope of the categories.

The decisions on the initial design of the bridge can substantially affect the selection of material and construction methods, thus influence the environmental performance over its long life cycle span. For example, the environmental impacts of designs with a single superstructure section showed overwhelming advantages than those with parallel double superstructures during the maintenance phase, while the steel composite bridges show preferable performances through the construction phase, mainly due to the avoided burdens from the formwork and scaffolding. Comparing to proposals 1 and 2, both of the proposals 3 and 4 require nearly double man hours and increased equipment. Besides, in contrast to proposal 1, the impact due to painting work contributes to almost double impact for proposal 2.

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